Fermi National Accelerator Laboratory

FERMILAB-Pub-78/20-THY
February 1978

Phenomenology of the New Light Higgs Boson Search

WILLIAM A. BARDEEN and S.-H. H. TYE
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

J.A.M. VERMASEREN
Department of Physics, Purdue University, W. Lafayette, Indiana 47907

ABSTRACT

We study the feasibility of two experiments to test the existence of the new light Higgs boson (Higglet) h: (1) The observation of Higglets produced in high energy proton reactions using the Bethe-Heitler process $h + Fe \to \ell^+\ell^- + Fe$ for detection; (2) The production of Higglets using a low energy intensive electron beam with detection using the two photon decay mode.

Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

In the recent past, a model of hadron physics has begun to emerge as something of a standard theory. This is the Yang-Mills theory of colored quarks and gauge fields, namely Quantum chromodynamics (QCD). The discovery of pseudoparticle solutions in QCD implies that parity (P) and time reversal invariance (T) in QCD are in general strongly broken.[1] Since P and T appear to be only weakly broken symmetries in nature, a puzzle is posed for this standard theory. Among the various resolutions to this problem, an attractive one is that proposed by Peccei and Quinn.[2] They showed that P and T conservation in strong interactions would be restored if the Lagrangian has a global U(1) chiral symmetry. It is natural to achieve this by combining strong, weak and electromagnetic interactions and then enlarging the Higgs boson sector of the Lagrangian. Subsequently Weinberg[3] and Wilczek[4] pointed out that one consequence of such a unified theory is the existence of a very light, weakly interacting pseudoscalar Higgs boson, which we shall call Higglet, h (as used in ref. 5; the name "axion" is used in ref. 3,4).

Some of its properties have been discussed by Weinberg,[3] Wilczek,[4] and Bardeen and Tye.[5] In particular Weinberg has examined existing experiments for evidence concerning the existence of the Higglet. He observed that the most stringent experiment is the reactor neutrino experiment where Higglets produced in the reactor would interact with deuterium to produce neutrons.[6]

The theoretical estimate of the neutron counts depends on the mixing of h and π_o. The strength of this mixing is rather model dependent. In the Weinberg-Salam model with two Higgs doublets, this is given for low energies by,[3,5]

$$\xi_\pi = \frac{1}{2}\frac{f_\pi}{f} B_\pi = 1.9 \times 10^{-4} B_\pi \tag{1a}$$

$$B_\pi = L(x + \frac{1}{x})\frac{m_d - m_u}{m_d + m_u} - x + \frac{1}{x} \tag{1b}$$

where $f_\pi \simeq 94$ MeV, $\sqrt{2}\,G_W f^2 = 1$; m_d and m_u are the current quark masses for the down and up quark respectively. L is a non-zero integer $L = N_p - N_n$ where N_p (N_n) is the number of 2/3 (-1/3) charged quarks coupled to the first Higgs doublet. x is the ratio of the vacuum expectation values of the two Higgs fields and can have any value, $0 < x < \infty$. However, we do not expect x to be vastly different from unity. The theoretical estimate of the neutron count is proportional to the production rate $\sigma(h)$ of h and the cross-section $\sigma(h + d \to p + n)$. It is estimated by Weinberg[3] to be $4 \times 10^5 \times B_\pi^{\ 4}$ counts/day as compared to the experimental bound of (-2.9 ± 7.2)/day.[6] If this estimate is valid[7] the existence of the Higglet (at least in the Weinberg-Salam model with two Higgs doublets) would be ruled out unless B_π can be small. Since there are large uncertainties associated with B_π and the Higglet production rate estimate[7] in a nuclear reactor,it is crucial that the search for experimental evidence for <u>or</u> against the existence of the Higglet should be continued. These searches are seen to be important when we realize that none of the known alternative resolutions[1-4] to this P and T invariance puzzle in QCD is either (1) more theoretically appealing <u>or</u> (2) more susceptible to experimental tests. Hence, to be able to rule out the existence of the Higglet is almost as important as its discovery.

Besides the nuclear reactor experiment discussed by Weinberg,[3] a number of other experimental tests on the existence of the Higglet have been suggested: $K^+ \to \pi^+ h$,[3,8] $J/\psi \to h\gamma$,[4] and $\Upsilon(9.4) \to h\gamma$.[3,4] The estimate of the $K^+ \to \pi^+ h$ decay rate is very model dependent. For example, if we assume that the octet enhancement effect in non-leptonic K decays is due to asymptotic freedom behavior at short distances,[9] the following branching ratio can be obtained using only the enhanced octet term in an effective weak interaction Lagrangian:[10]

$$\mathrm{BR} = \frac{\Gamma(K^+ \to \pi^+ h)}{\Gamma(K^+ \to \mathrm{all})} = \frac{1}{2}\sqrt{2}\, G_W f_\pi{}^2 \left(x - \frac{1}{x}\right)^2 \frac{\Gamma(K_S \to \pi^0 \pi^0)}{\Gamma(K^+ \to \mathrm{all})}$$
$$= 3 \times 10^{-6} \left(x - \frac{1}{x}\right)^2 \qquad (2)$$

to be compared to the experimental bound of $\mathrm{BR} \lesssim 0.27 \times 10^{-6}$.[8] Unfortunately this prediction for the branching ratio cannot be uniquely obtained using only $SU(3) \times SU(3)$ current algebra.

We note that $K^\pm$, J/ψ and Υ decays do not provide direct evidence for the possible existence of h since the Higglet produced from the decay is left undetected. In this paper we discuss the feasibility of two experiments which may provide a more direct detection of a Higglet. One is an experiment where a beam of high energy Higglets is produced. The Higglets are then detected via a Bethe-Heitler type of reaction. The other experiment uses the production of a low energy beam of Higglets which then decay into two photons.

Experiment 1

Let us consider the production of a lepton pair in the reaction

$$h + Fe \to \ell^+\ell^- + X \tag{3}$$

via a Bethe-Heitler mechanism as shown in Fig. 1a. The coupling strength of the $\ell^+\ell^-h$ pseudoscalar vertex is given by $2^{1/4}\sqrt{G_W}\, m_\ell\, c_\ell$ (where $c = \frac{1}{x}$ or $-x$). For the type of reactions and the energies under consideration, the coherent production process gives the dominant contribution.[11] It is straightforward to calculate this cross-section numerically. The results are summarized in table I for a Higglet mass of 100 keV and the leptons taken to be muons. For very high Higglet energies, the cross-section is insensitive to the precise value of the Higglet mass. The small $\mu^+\mu^-$ invariant mass and the extremely small energy transfer to the target provide a clear signature for this Higglet induced reaction as can be seen in table I. In general the asymptotic cross-section scales like

$$\sigma \sim c_\ell^{\,2} G_W \ln \frac{s}{m_\ell^{\,2}} \tag{4}$$

where s is the C.M. energy squared.

Let us take some typical values to estimate the number of $\mu^+\mu^-$ pair events expected. With 10^{17} protons at 400 GeV we expect roughly (with about 4 neutral pions per proton) $B_\pi^{\,2}\left(\frac{f_\pi}{2f}\right)^2 4 \times 10^{17}$ Higglets to be produced via π^0-h mixing. Taking an average cross-section of $1.6 \times 10^{-36}\, c_\mu^{\,2}\mathrm{cm}^2$/Nucleon and a $2\,\mathrm{kg/cm}^2$ detector, we conclude that $30(c_\mu B_\pi)^2$ $\mu^+\mu^-$ pair events per 10^{17} protons should be observed provided all Higglets go through the detector and no events are lost due to limited counter efficiencies. If $(c_\mu B_\pi)^2$ is of order unity, the experiment should be feasible. Weinberg's estimate of the nuclear reactor bound requires $B_\pi^{\ 2} < 10^{-2}$ for low energy Higglets. From Eq. (1), it is clear that x must then be of order unity. If we naively assume that $(c_\mu B_\pi)^2 \simeq 0.01$ for high energy Higglets, we expect one $\mu^+\mu^-$ event per 3×10^{17} protons.

For the high energy Higglet reactions, B_π as given by Eq. (1) may not be valid. However, we can derive a lower bound on B_π by using the bare Higglet-current quark coupling. This gives $B_\pi^{\ 2} \gtrsim 10^{-3}$. Also for very small B_π, the h–η coupling B_η would contribute significantly to the production of Higglets. Hence if an experimental bound of $(c_\mu B_\pi)^2 < 10^{-3}$ can be obtained, the existence of Higglets would be extremely unlikely.

This test can be done as a "beam dump" experiment. However, a search among the already available di-muon pairs obtained in neutrino experiments would be very useful. A search of electron pairs with zero opening angle and no other visible energy in the bubble chamber may be useful provided any π^0 background via neutral current events is understood.

Experiment II

Although the mass of the Higglet is quite model dependent its lifetime can be more reliably estimated (at least for the Weinberg-Salam model with standard Higgs couplings[5]):

$$\tau\ (h \to 2\gamma) \ \simeq\ 0.8\left(\frac{100\ \mathrm{keV}}{m_h}\right)^5 \mathrm{sec.} \qquad (5)$$

where we have assumed $m_h < 2m_e$. This long lifetime--$\sim$30 sec. to 10^{-5} sec. for m_h ranging from 50 keV to 1 MeV--suggests the use of very low energy Higglets to observe their decay into two photons. The Higglets can be produced by a very intense low energy electron beam according to the process pictured in figure 1b.[12] One can look for decaying Higglets by placing a photon detector sufficiently far downstream. An advantage of this experiment is that the theoretical estimates are independent of hadronic models resulting in parameters like B, since the Higglet production mechanism is understood. The h-e pseudoscalar coupling strength is $2^{1/4}\sqrt{G_W}\, m_e c_e$ where c_e is expected to be of order unity. The cross section $\sigma(ep \rightarrow ehp)$ is evaluated numerically and summarized in table II, where form factors, multiple scattering and screening effects are not included. For a 100 keV Higglet one can fit the cross-section by the formula

$$\sigma \simeq (0.023 \ln E - 0.005) c_e^{\,2} \tag{6}$$

σ in pb and E in MeV. This formula is valid for incoming electrons with energies larger than 5 MeV. Another interesting phenomenon is that the angle, $\theta_{1/2}$, within which 50% of the Higglet produced can be found is given by the empirical formula

$$\theta_{1/2} \simeq \frac{0.54}{E_{beam}} \,\mathrm{rad} \qquad (E \text{ in MeV}) \quad . \tag{7}$$

This formula is for 100 keV Higglets. For heavier Higglets the constant is somewhat larger (e.g. $\simeq 0.75$ for a 1 MeV Higglet). Assuming $\langle E_h \rangle / E_{beam}$ to be about constant as can be verified in table II one can see that the effects of the time dilation factor E_h/m_h and Eq. (7) cancel each other if one puts the photon detector at such a distance that half of the Higglets will go through it. Consequently, beam energy is not the prime consideration in doing this experiment.

To estimate the feasibility of this experiment, let us do a sample calculation for 100 keV Higglets. With lead as a target and a 1 mA current of 20 MeV electrons we expect a production rate of about $8 \times 10^4 c_e^{\,2}$ Higglets per second. The average energy of these Higglets is roughly 12 MeV. The rate of two photon counts becomes $2.2\, b\, c_e^{\,2}$ per day where b (in meters) is the diameter of the counter being used, placed at a distance $d = (E_{beam} \times b)/(2 \times 0.54)$ meters (E_{beam} in MeV). For heavier Higglets the production cross-section goes down somewhat, the beam is slightly wider and the Higglet energy is a slightly larger fraction of the beam energy but these effects are roughly cancelled by the changed time dilation factor. If one takes the mass dependence of the lifetime into account, it is clear that a heavier Higglet will lead to much larger counting rates, which is roughly represented by $2 \times 10^5 \times b \times c_e^{\,2} \times m_h^{\,5}$ counts per day (m_h in MeV).

A negative result in an experiment like this will therefore put severe restrictions on the possible values of m_h.

A low energy Higglet beam can also be produced via low energy proton-nucleus scattering. However, this production rate depends on the uncertain $B_\pi^{\,2}$. In table II we also include the Higglet production cross-section from a high energy electron beam. In this case the detection of Higglets can be via the Bethe-Heitler process described earlier.

Another experiment that may be possible is the production of Higglets via the Primakoff effect. Its cross-section scales like:

$$\sigma \sim \Gamma_{h\to\gamma\gamma}\, (m_h)^{-3} \ln \frac{s}{m_h^{\,2}} \quad . \qquad (8)$$

This can easily be compared with π^0 production leading to the ratio

$$\frac{\sigma_h}{\sigma_{\pi^o}} \simeq 2\frac{\tau_{\pi^o}}{\tau_h}\left(\frac{m_{\pi^o}}{m_h}\right)^3 \sim 6\times 10^{-7}\left(\frac{m_h}{100\text{ keV}}\right)^2$$

where we assumed the logarithms to account for about a factor 2. This experiment suffers however from the relatively low intensity of available photon beams.

In conclusion, we would like to say that due to the uncertainties in the theory it would take a combination of experiments, all with negative results, to rule out the existence of the Higglet. In case it is discovered it would be important to determine the parameters B, x, $(N_p - N_n)$ and m_u/m_d by carrying out the various experiments.

ACKNOWLEDGMENTS

We thank R.D. Peccei and J. Yoh for very useful discussions. We thank C. Quigg for reading the manuscript.

REFERENCES AND FOOTNOTES

[1] A.A. Belavin, et al., Phys. Lett. 59B, 85 (1975); G. t'Hooft, Phys. Rev. D14, 3432 (1976); R. Jackiw and C. Rebbi, Phys. Rev. Lett. 37, 172 (1976); C.G. Callan, R.F. Dashen and D.J. Gross, Phys. Lett. 63B, 334 (1976).

[2] R.D. Peccei and H.R. Quinn, Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D16, 1791 (1977).

[3] S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).

[4] F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

[5] W.A. Bardeen and S.-H.H. Tye, Fermilab-Pub-77/110-THY.

[6] H.S. Gurr, F. Reines and H.W. Soble, Phys. Rev. Lett. 33, 179 (1974). Ref. 3 also includes two other less stringent bounds on $he \to \gamma e$ and $h \to \gamma\gamma$. These two bounds are proportional to $B_\pi^{\ 2}$ (from the Higglet production).

[7] The rate of Higglet production in nuclear reactor may be substantially smaller than that given in ref. 3 (even with $B_\pi^{\ 2} = 1$). A more detailed analysis has been carried out by R.D. Peccei (private communication).

[8] See e.g. T. Goldman and C.M. Hoffman, Phys. Rev. Lett. 40, 220 (1978).

[9] M.K. Gaillard and B.W. Lee, Phys. Rev. Lett. 33, 108 (1974); G. Altarelli and L. Maiani, Phys. Lett. 52B, 351 (1974).

[10] W.A. Bardeen and S.-H.H. Tye (unpublished). The branching ratio is given for the Weinberg-Salam model with standard Higgs coupling.

[11] e.g. Y.S. Tsai, Review of Modern Physics 46, 815 (1974).

[12] The 2 photon production (i.e. Primakoff production by the field of the incoming electron) has been computed to be smaller than the processes of figure 1b by 2 to 3 orders of magnitude.

TABLE CAPTIONS

Table I: The cross section per nucleon, the average invariant mass of the μ pair and the average energy transfer to the target for the reaction $hF_e \rightarrow \mu^+\mu^- F_e$ with $c_\mu^2 = 1$. Screening and multiple scattering effects are not included.

Table II: The cross section, the average Higglet energy and $\theta_{1/2}$, the angle within which 50% of the Higglets are emitted for the bremstahlung process $ep \rightarrow hep$ with $c_e^2 = 1$. Form factors, screening and multiple scattering effects are not included.

Table I

e_h in GeV	$\sigma_{hF_e \to \mu^+\mu^- F_e}$ in pb per nucleon	$\langle M_{\mu^+\mu^-} \rangle$ in MeV	ΔE_{target} in keV
1	0.012	280	88
3	0.15	310	44
5	0.38	330	35
10	1.01	350	24
20	2.3	380	19
40	4.1	400	15
100	7.0	430	12
200	9.3	450	9

Table II

E_{beam} (MeV)	m_h (MeV)	$\sigma_{ep\to hep}$ (pb)	$\frac{\langle E_{Higglet}\rangle}{E_{beam}}$	$E_{beam} \times \theta_{½}$ (MeV . rad)
10	0.1	0.047	0.56	0.53
20	0.1	0.063	0.61	0.56
50	0.1	0.087	0.64	0.53
100	0.1	0.102	0.65	0.54
10^4	0.1	0.21	0.65	0.53
10	0.5	0.019	0.68	0.65
20	0.5	0.028	0.73	0.69
50	0.5	0.040	0.74	0.64
100	0.5	0.052	0.75	0.61
10^4	0.5	0.12	0.80	0.65
20	1.0	0.012	0.77	0.79
10^4	1.0	0.062	0.83	0.68

FIGURE CAPTIONS

Fig. 1a: The Bethe-Heitler production of a lepton pair by a Higglet in the presence of an iron nucleus.

Fig. 1b: The radiative production in lowest order of a Higglet due to an electron passing through matter.

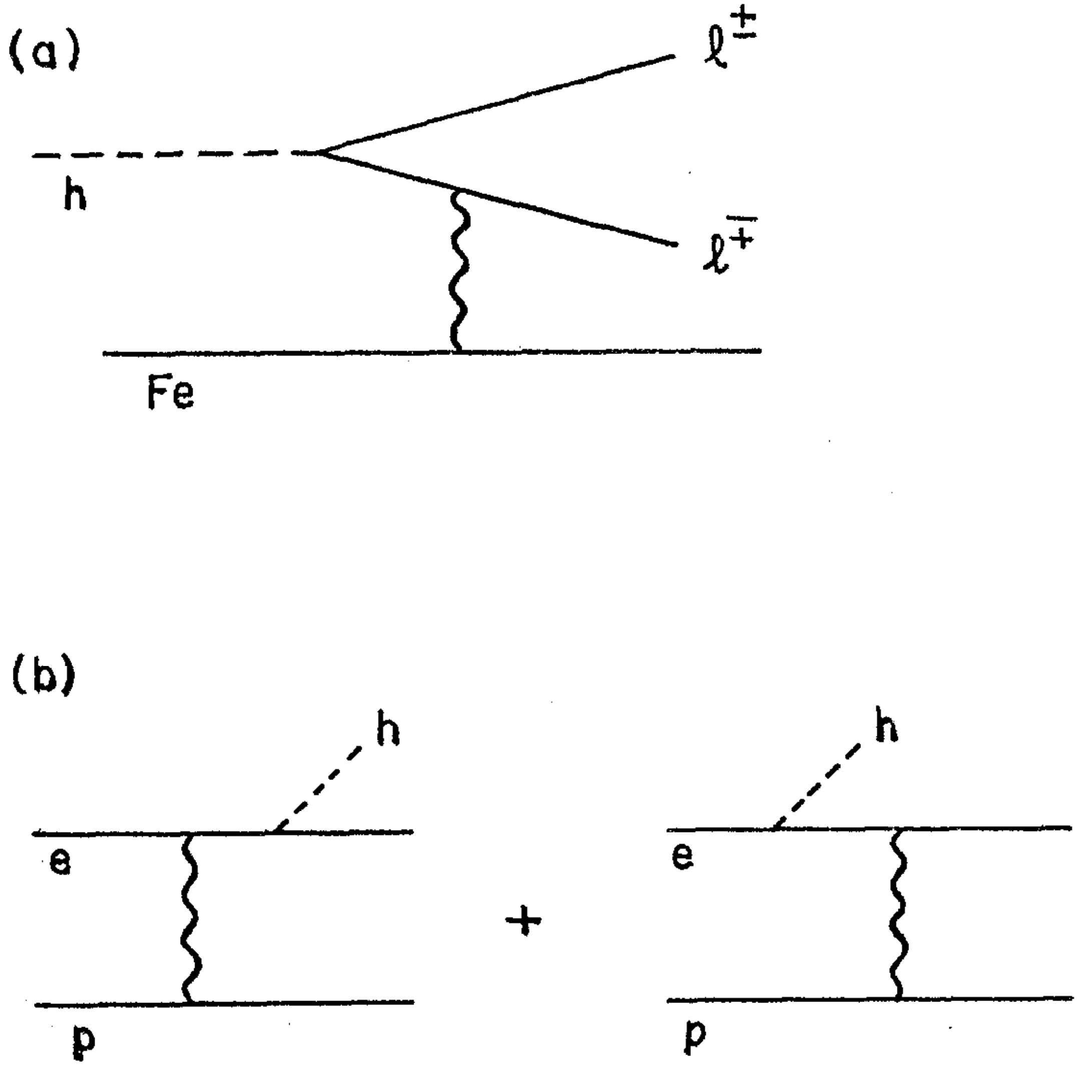

Fig. 1